HIGH SPEED, LARGE MOTION ELECTROSTATIC ARTIFICIAL EYELID

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ABSTRACT

The fabrication, testing and performance of a new device for the protection of optical sensors will be described. The device consists of a transparent substrate, a transparent conducting electrode, insulating polymers, and a reflective top electrode layer. Using standard fabrication techniques, arrays of apertures can be created with sizes ranging from micrometers to millimeters. A stress gradient resulting from different thermal coefficients of expansion between the top polymer layer and the reflective metal electrode, rolls back the composite thin film structure from the aperture area following the chemical removal of a release layer. The application of a voltage between the transparent conducting and reflective metal electrodes creates an electrostatic force that unrolls the curled film, closing the artificial eyelid. Fabricated devices have been completed on glass substrates with indium tin oxide electrodes. The curled films have diameters of less than 100μm with the arrays having fill factor transparencies of over 80%.

INTRODUCTION

First generation MEMS devices for the protection of optical sensors have been fabricated and tested. These devices, which function as artificial eyelids, use electrostatic operation to produce large, fast motions for opening and closing an aperture above an optical sensor. The actuator is based on the electrostatic attraction of a flexible, curled film to a substrate. One core issue for the actuation of microfabricated structures is the desire to achieve large motions with strong forces and fast actions while requiring low power. Existing actuation methods based on thermal, electromagnetic and piezoelectric processes all have limitations in either the speed of the actuation, range of motion, or required power. Most electrostatic actuation techniques also are limited in the range of motion available. The new actuator structure, used in the artificial eyelid, greatly extends the range of motion available while maintaining reasonable voltages and the other advantages of electrostatic actuation such as low power, strong force, and high speed. The structure can easily be fabricated in arrays where the actuators can all be activated at once to protect the entire optical sensor, or individually to protect selected areas of the sensor. Alternative configurations of the actuator can be fabricated to control a variety of other things, such as electrical current, gas flow, and electromagnetic fields.

The application of the artificial eyelid for the protection of optical sensors is driven by the need of the military to ensure that the imaging information of a battlefield is not lost by damage to a sensor. The widespread use of lasers on the battlefield results in a significant risk of damage both by intentional action and by chance. The artificial eyelid system under development is intended to protect infrared imaging systems from laser damage by quickly inserting a reflective, opaque film into the light path of the sensor upon the detection of a threat. When the artificial eyelids are open, the transmission loss of the eyelid needs to be minimized for maximum sensitivity of the sensor.

PRINCIPLE OF OPERATION

The electrostatic flap is a curled, flexible film with one electrode in the film and a second electrode fixed in the substrate. The flap is attached to the substrate at one edge and there is at least one insulating film covering the electrodes to prevent their coming into contact with one another, as shown in the cross-section of the basic actuator in Figure 1. The basic operation of the flap is simple; a voltage applied between the two electrodes establishes an electrostatic attraction. The force is strongest at the point where the flexible film attaches to the substrate. As the electrostatic force overcomes the material system rigidity, the flexible film begins to unroll, moving the point of contact between the flexible film and the substrate, and subsequently establishing a new area of high field strength. This process continues until the entire film has unrolled against the substrate. The maximum force when the flap is completely unrolled is proportional to the area of the flap, the square of the applied voltage, and inversely proportional to the thickness of the dielectric film between the fixed and flexible electrodes.

An actuator with a square flap 80 μm on a side, with a polyimide dielectric thickness of 0.5 μm, and 50 V applied to the electrodes has an attractive force of 1 mN. Upon the removal of the applied voltage, the stress in the flexible film curls the material stack back to its original position. The stress in the film can be controlled during the metal deposition process or induced by post-deposition annealing. This configuration has some

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interesting and unique properties for MEMS. Because it is electrostatic in operation, the power requirements are very low compared to thermal and electromagnetic actuators. The small separation at the point of attachment results in strong forces, while the curling of the film positions the tip far from its unrolled position on the substrate. Thus the electrostatic actuator has a large range of motion while maintaining strong forces and operating at lower voltages than other electrostatic actuators with equivalent motions. Because the film releases with the removal of the applied voltage with a curling motion, the separation occurs along a line instead of the entire area of contact. Thus stiction is not an issue since the stress of the film is larger than the attractive surface forces along the line where the film separates from the substrate. In other electrostatic actuators that have planar, rigid structures attracted to the substrate, the entire area of the suspended structure and substrate must be separated at one time, which can lead to stiction.

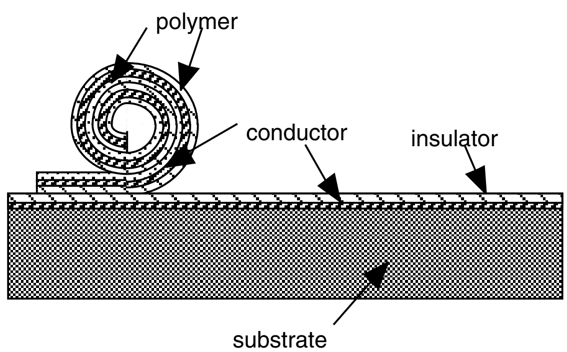

Figure 1. Cross-sectional drawing of an electrostatic flexible film actuator.

The concept of the flexible film actuator was developed over 20 years ago by Kalt [1] who applied it to large displays constructed from arrays of individual electrostatic actuators measured in inches. A few researchers have investigated the flexible film actuator constructed from inorganic materials [2-4]. We have recognized the versatility, advantages, and large number of markets in which a polymer flexible film, electrostatic MEMS actuator can be applied [5,6]. The actuator can be fabricated on many different types of substrates such as silicon, glass and plastics. In its simplest form, the flexible film actuator can be arrayed to create a display, a shutter, a spatial light modulator, or to alter the reflective properties of a surface. An array of the actuators on a surface can alter the flow characteristics of a gas over the surface. With the appropriate patterning of the layers the actuator can be used as an electrical relay.

ARTIFICIAL EYELID FABRICATION

The fabrication of the electrostatic, flexible film uses polymer and metal depositions and etches [5]. The creation of the artificial eyelid places some additional constraints on the design and fabrication of the device. First, the substrate needs to be transparent to the frequencies detected by the optical sensor. In a similar manner the conductor that is deposited on the substrate for the fixed electrode and the insulator layer on top of it need to be transparent. Second, the films and their thicknesses used in the rolled up flexible film, need to be chosen to produce a small enough diameter to maximize the transmission of the light through the eyelid array when the array is open.

The first generation of devices were fabricated at MCNC on aluminum silicate glass substrates with an indium-tin-oxide (ITO) film for the conductive electrode. While this combination of substrate and electrode material is not transparent very far into the infrared (absorbing beyond approximately 2µm wavelengths), it was chosen to provide a quick test of the concept of an artificial eyelid and to allow the development of the tightly rolled flexible film. Future fabrication runs of devices will be done with different substrates and electrode materials that are more transparent to infrared. Measurements of the IR transmission of a 6.7 µm thick polyimide film show transmissions of over 95% in the wavelength range of 3-5 µm with a slight absorption peak at 3.3 µm (down to 88% transmission). With the use of a glass substrate, the use of a deposited oxide film could not be used for the sacrificial layer since the HF would attack the substrate as well as the ITO. Instead an aluminum film was used for the sacrificial layer. The etch time is slower than for the combination of SiO_2 and HF. Typically the substrates are left in the aluminum etch for 48 hours to ensure that all the aluminum is removed.

To create the tightly rolled flexible films, the thicknesses of the polyimide, chrome, and gold layers need to be carefully chosen. In these films, the curling stress arises from the curing of the polyimide at 400°C and the larger thermal expansion coefficient of the polyimide compared to the metal film. Prior to the curing of the polyimide, it is still soft and easily deformed. The cure at 400°C hardens the polyimide and the cool down from the 400°C temperature results in the polyimide attempting to shrink more than the gold film, giving rise to the curling stress. The bottom layer of polyimide should be as thin as possible from the point of view of the diameter of the roll, but thick enough to provide sufficient electrical isolation in combination with the insulator layer deposited on top of the fixed electrode on the substrate. The chrome thickness should be very thin, just enough to provide adhesion between the gold and the polyimide. The gold layer also should be thin, enough to provide electrical continuity and optical opaqueness. Gold was chosen for its ductile properties so that long lifetimes could be obtained without crack formation. The top layer of the polyimide should be thick enough to produce the shrinkage induced curl but thin enough to keep the film flexible. Modeling of the curl showed that thinner bottom polyimide layers and gold layers result in tighter film radii, and there is a minimum in the radii as a function of the top polyimide thickness. Measured diameters of fabricated rolled films range from less than 100μm to over 200μm and match the model.

Figures 2 and 3 show SEM photographs of the completed devices. Figure 2 shows several arrays of shutters with each array approximately 4mm on a side. Measurements of the fill factor due to the rolled up shutters and metallizations show transparencies of over 80%. The different nature of the rolls is due to the designed variations of the shutters at the hinge attachment points and in the shutter flaps. The photo shows good uniformity of the shutters within the arrays. Figure 3 shows a side view of the rolled up films.

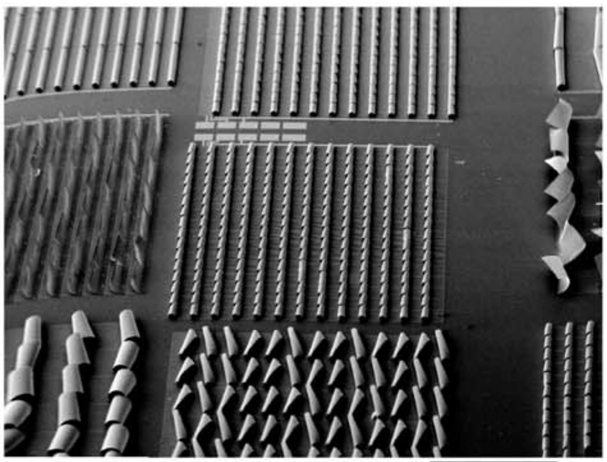

Figure 2. SEM photograph of several arrays of shutters.

RESULTS OF SHUTTER OPERATION

Testing of the artificial eyelid demonstrated that the devices functioned as they were designed, rolling out with the application of a voltage between the fixed electrodes and the flexible electrodes. The operating voltage ranges from 100V to 300V. This is higher than was expected or desired. The variation in the voltages to close the shutters is a function of the geometry of the flap at the attachment point to the substrate. The device shown in Figure 3 requires a large voltage to close, and the cause can be seen in the angle between the substrate and the flexible film where it attaches to the substrate. The angle is approximately 35° instead of the tangential configuration that was anticipated. Because of the increased angle, the separation between the flexible film and the substrate increases rapidly with increasing distance from the attachment point. With the electrostatic force being inversely proportional to the square of the distance between the electrodes, the attractive force is greatly reduced. The large exit angle is due to the anchoring of the flap at the hinge, which limits the ability of the polyimide at the anchor point to curl from the temperature induced shrinkage. To relieve the thermally induced stress in the anchor region, the immediately adjacent polyimide that is part of the released film, is pulled toward the anchor region. Devices that have a more tangential attachment operate at the lower values of voltage. These devices have modifications in the film structure that result in a locally large radius of curvature. These modifications are either due to increased mechanical stiffness or decreased thermally induced stress. As a result, the separation between the flexible electrode and the substrate is reduced and a lower voltage is sufficient to unroll the film across the substrate.

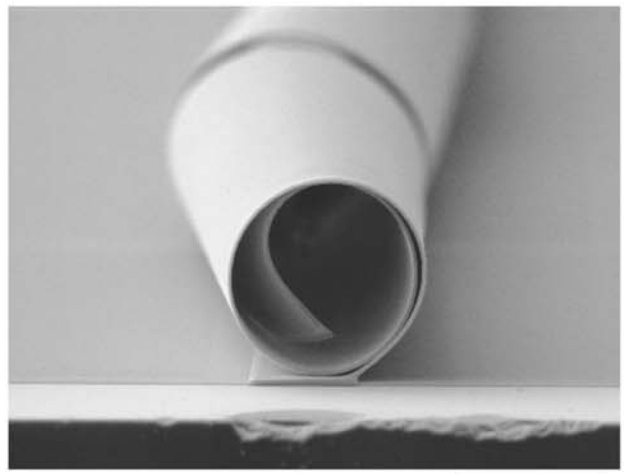

Figure 3. SEM photograph of rolled up shutter.

Figure 4 shows a plot of the operating voltage as a function of the exit angle for a variety of devices from two different wafers. The exit angle was measured from cross sectional SEM photographs. The devices were chosen that would have the same radii on each wafer but they have different dimensions and different anchor region designs. There is a fair amount of scatter in the data due to the limited data set but the general trend is visible where decreasing operating voltage occurs with decreasing exit angle. The two wafers had different thicknesses of the gold and polyimide in the flexible films. The devices on the wafer with the more flexible film have the lower operating voltages. Another general observation made to date is that the devices with the reduced thermally induced stress have lower operating voltages than the devices where the film was mechanically stiffened at the attachment point.

The lifetimes of the devices depend on the radius of curvature and hence the operating voltage, and on the size of the device. Larger radius devices with correspondingly lower operating voltages (100-150V) possessed lifetimes over 450 million cycles. Smaller radius devices have shorter lifetimes due to the higher operating voltages and the resulting dielectric breakdown. Longer devices can effectively snap the ends of the closing curls like a whip, which significantly shortens the lifetime through the creation of cracking and fraying of the films. New device designs and alternative materials are being evaluated to reduce mechanical degradation and dielectric breakdown.

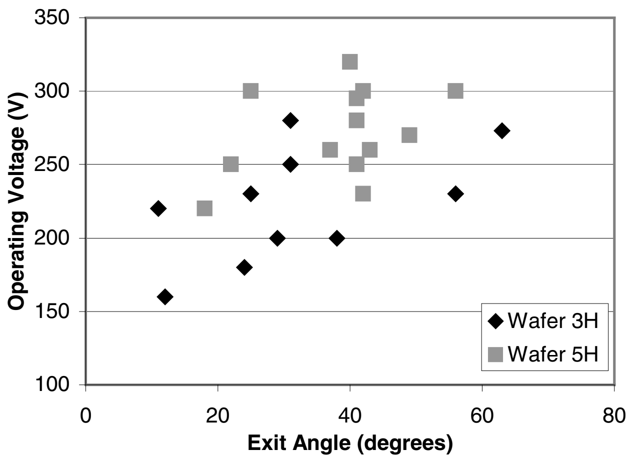

Figure 4. Plot of the operating voltage as a function of the exit angle for devices on two wafers. Wafer 3H had bottom polyimide, gold, and top polyimide thicknesses of 0.5µm, 50nm, and 0.7µm respectively. Wafer 5H had thicknesss of 0.5µm, 100nm, and 1.0µm respectively.

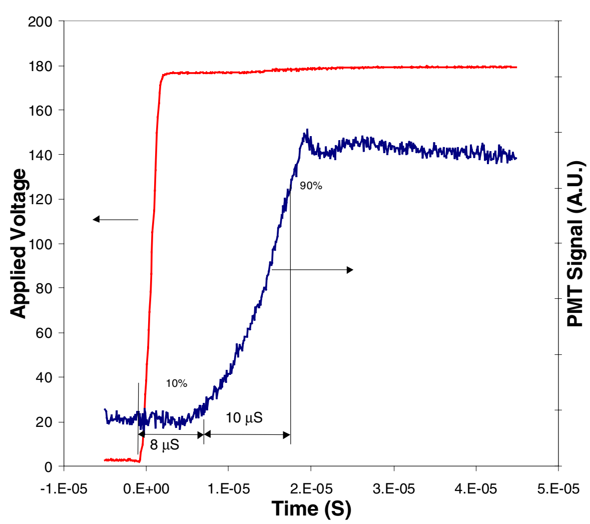

Figure 5. Measured closing of a shutter in response to a voltage step.

Optical measurements were made on devices to determine the speed of operation of the shutters. A square wave pulse was applied to the device, and a photodetector monitored the transmission of the light generated by a laser. Figure 5 shows the applied voltage and photodetector signals with the closing of a shutter. The optical response can be broken into two time periods. The first time period of 8 µsec after the start of the voltage pulse shows little change in the position of the shutter. Part of this time is due to the rise time of the voltage pulse while the rest is the attraction of the rolled flexible film down to the substrate. The second time period of 10 µsec shows the closing of the shutter at an accelerating pace.

CONCLUSIONS

The first generation of artificial eyelids for sensor protection have been fabricated and tested. The artificial eyelids use a flexible curled film electrostatic actuator, which is a MEMS actuator capable of large motions with high speed and strong forces. Devices have been fabricated using gold, chrome, polyimide, and aluminum with standard processing techniques. The shutters close with the application of 100 to 300V. The required voltage to close the devices depends on the geometry of the flexible film adjacent to the attachment point. Devices with larger exit angles require larger voltages. Measurements show that the devices close within 18µsec from the start of a voltage step. Devices with lifetimes of over 450 million cycles have been tested. Additional fabrication runs are scheduled to improve the IR transmission and the lifetimes of the devices. The flexible curled film actuator looks promising for applications for the protection of optical sensors as well as for several other types of applications.

ACKNOWLEDGMENTS

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